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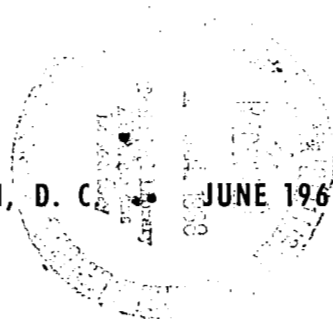
AN EXPLANATION OF FITZGERALD'S AUDIOFREQUENCY RESONANCES AND SOUND BEAMS

by Donald R. Behrendt and James P. Cusick

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION • WASHINGTON, D. C. • JUNE 1968





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ABSTRACT

Fitzgerald's method is used to investigate the origin of his audiofrequency resonant phenomena. The source of the phenomena is shown from experiment to arise from the stiffness of the sample-shaker interface and not from a process associated with the interior of the sample, as proposed by Fitzgerald. The resonance effects are explained in terms of conventional elastic theory.

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SUMMARY

An experimental examination of Fitzgerald's method for observing audiofrequency resonances is presented. The low kilohertz resonance effects are a consequence of the low stiffness coupling of the sample and shaker. The phenomena bears no direct relation to the sample bulk properties, and the effect is explained in terms of conventional elastic theory.

INTRODUCTION

Fitzgerald (refs. 1 and 2) has described an apparatus, as shown in figure 1, with which he measures audiofrequency resonances and sound beams in crystals. The apparatus consists of a piezoelectric disk, which is made to vibrate axially by applying an alternating voltage to its silvered faces. On this disk is placed a sample of the material to be investigated. An ordinary high-fidelity phonograph cartridge stylus is placed against the sample in such a manner that the vertical motion of the sample can be observed as a voltage produced by the cartridge. This voltage is recorded as a function of vibration frequency. With the cartridge stylus touching the sample, Fitzgerald observed (fig. 2) one or more peaks (which he calls resonances) in the output voltage against frequency; however, with the stylus in contact with the surface of the piezoelectric disk, the output voltage is relatively independent of the driving frequency, and no large peaks are observed. Fitzgerald (refs. 1 and 2) has reported observing resonances when the samples tested were coins, 1/4- and 1/2-inch (0.635- and 1.27-cm) cubes, and right circular cylinders. He attributes these resonances to what he calls "internally generated particle waves." Similar resonance effects have been observed by Gotsky and Stearns (ref. 3) who used an apparatus resembling Fitzgerald's. They explain their

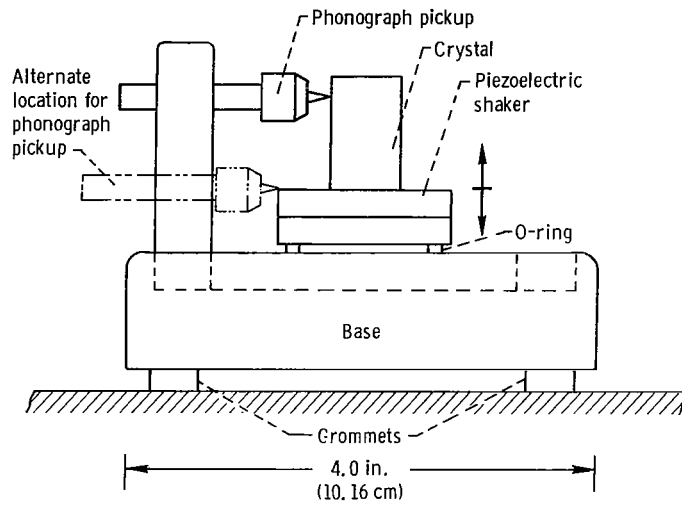


Figure 1. - Schematic drawing of experimental arrangement used by Fitzgerald (ref. 1). Any motion which occurs between the base and the stylus is reported to be a sample property.

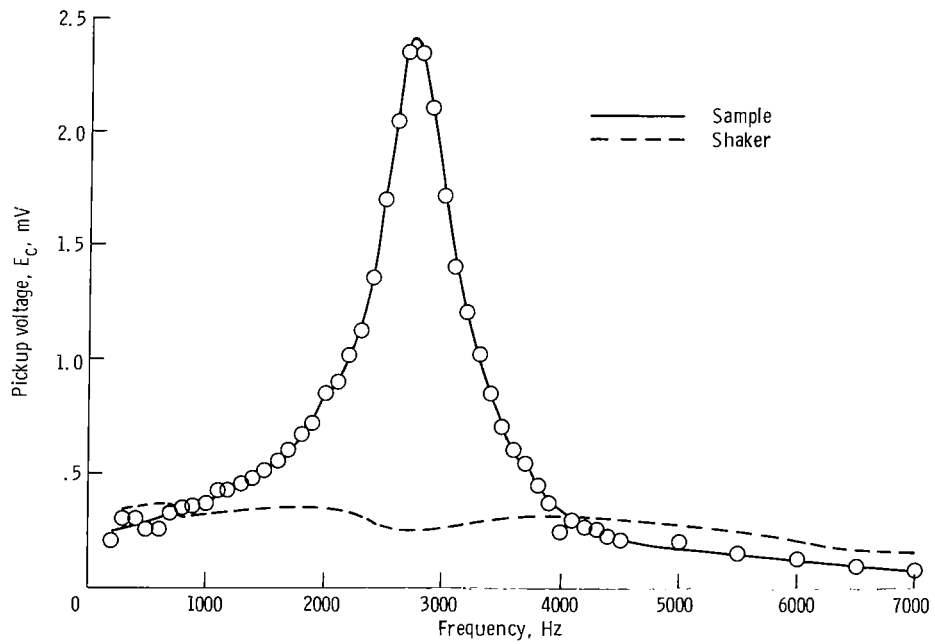


Figure 2. - Fitzgerald's (ref. 1) comparison of pickup voltages obtained with stylus contacting sample (a silver-copper alloy coin resting on edge) and shaker surface. Pickup voltage is proportional to displacement.

resonances in terms of a slip mechanism involving slip along one or more sets of slip planes in the sample.

This report presents an explanation of the Fitzgerald resonances in terms of a contact theory which uses conventional elastic concepts. This explanation is supported by experimental evidence. Also, a few observations are given on reported experimental results which point up the errors in Fitzgerald's analysis and in his experiment.

EXPERIMENTAL RESULTS

In Fitzgerald's experiment, the sample and driver are not rigidly connected. As a consequence, the sample is not constrained to move as Fitzgerald or Gotsky and Stearns propose, but rather many additional sample motions can occur. A meaningful analysis of the Fitzgerald experiment would require a detailed knowledge of the surface roughness as well as a knowledge of the particular vibrational mode of the sample at each frequency of interest. These difficulties can be circumvented by a direct experimental approach which demonstrates clearly that the origin of the Fitzgerald resonances is associated with the contact region of sample and driver. The experimental method of this report increases the stiffness of the contact region by use of a hard epoxy cement to couple the sample and shaker.

Experiments of the Fitzgerald type were performed with the apparatus used by Gotsky and Stearns which is similar to that shown in figure 1. In these experiments two sodium chloride (NaCl) samples were used: the first was cemented to the driver with a hard epoxy cement; the second was placed upon the driver in the manner of Fitzgerald. The samples measured $1/4$ by $1/4$ by $3/4$ inch (0.635 by 0.635 by 1.905 cm). Sample faces were cleavage planes. The output voltage of the phonograph cartridge was plotted in decibels against the frequency of the driver voltage. The results are shown in figure 3. Curve A is the response of the piezoelectric driver; curve B is the response of the cemented NaCl single crystal with the stylus located on the side face near the top surface; and curve C is the response of the NaCl single-crystal sample which was not cemented to the driver. Curve C displays a large resonance of the Fitzgerald type near 2 kilohertz. The results presented in figure 3 are representative of all observations made in this study; the cemented sample shows no unusual effects; the loose sample shows single or multiple resonances in the low kilohertz range depending on stylus position.

One of the simplest vibrational modes of the experimental arrangement of figure 1 is an axial mode in which the sample is a rigid body and the contact region of sample and shaker is a spring. The resonant frequency of this mode increases with increasing

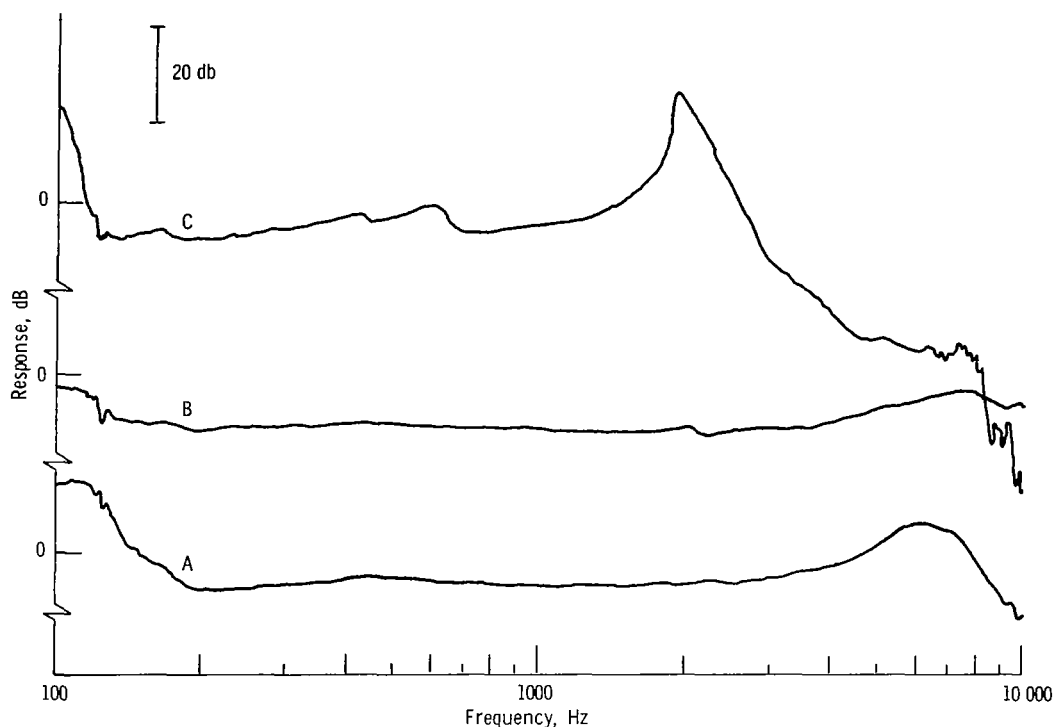


Figure 3. - Logarithm of output voltage in decibels against frequency of voltage applied to driver for three cases.

stiffness of the contact region. If the sample is rigidly attached to the driver with a hard epoxy cement, the stiffness of the contact region is high, and the resonant frequency of this mode would be near 30 kilohertz. If the sample is loosely coupled to the shaker surface (as in Fitzgerald's experiment), the stiffness of the sample-shaker interface is much lower because of surface roughness, and the resonant frequency would be reduced to the low kilohertz region. The experimental data of figure 3 display the effect of sample-shaker interface stiffness on resonant frequency. In curve B of this figure, the axial mode is above 10 kilohertz. The Fitzgerald experimental method is not suited to measure resonant modes above 10 kilohertz because of the frequency response and resonant properties of both the phonograph cartridge and the piezoelectric shaker.

DISCUSSION

Using a method which differs slightly from that of Fitzgerald, Hopkins (ref. 4) observes low kilohertz resonances. Hopkins' apparatus consists of a spherical sample mass resting on a flat base plate with a magnetic bar resting on top of the spherical sample. System vibrations are induced by magnetic coupling to the bar and resonances are detected by ear. Hopkins analyzes his experiment in terms of a two-mass - two-

spring model. The masses are the spherical sample and the magnetic driver. The springs are formed by the contact between the sphere and the base plate and the contact between the sphere and the driver bar. Hopkins computes the spring stiffness from equations describing the elastic deflection of a sphere-plate contact. Using these stiffness values, he obtains reasonable agreement between experimental and calculated resonant frequencies for several sphere sizes. Hopkins suggests that the resonance results of Fitzgerald may be explained in a similar manner and may not require the quantum mechanical considerations of Fitzgerald.

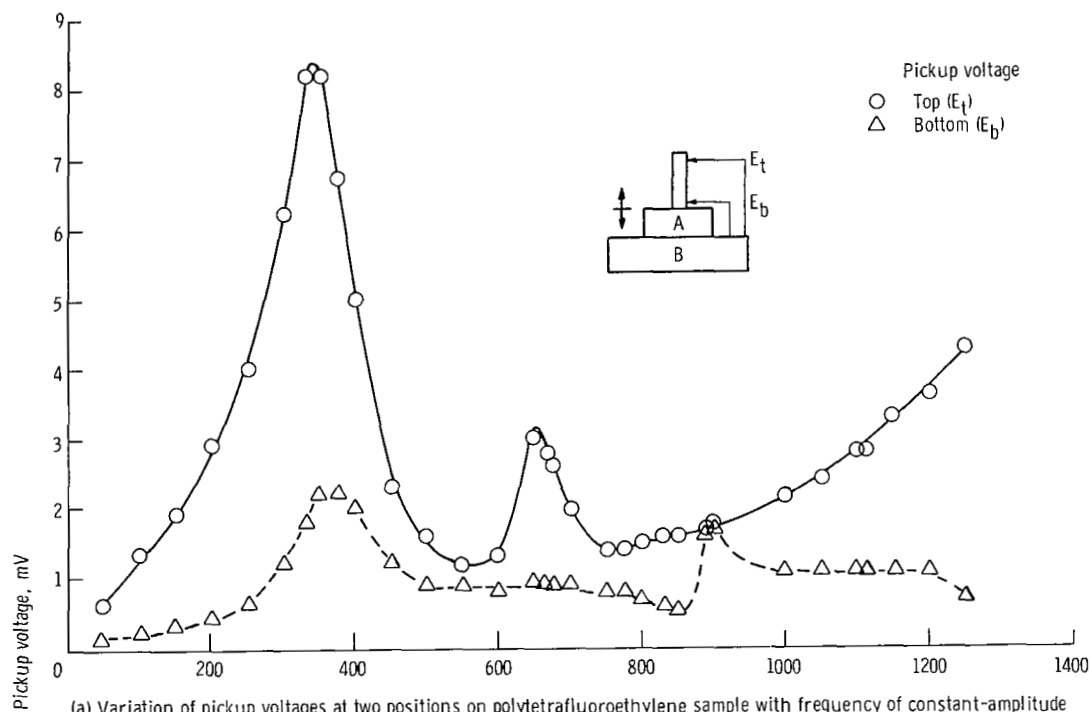
Hopkins reports another experiment in which the spherical sample is removed so that the magnetic bar rests on the flat base plate. Hopkins reports observing a resonance at 3736 hertz. Fitzgerald (ref. 5) analyzes this experiment by Hertzian contact theory and predicts a resonance at 38 000 hertz. The order-of-magnitude differences between observed and predicted frequencies leads Fitzgerald to conclude that Hertzian contact theory cannot explain either his own experimental results or Hopkins' bar-plate experimental results.

Fitzgerald (ref. 5) raises two objections to Hopkins' contact region interpretation of the resonances: (1) the inadequacies of Hertzian contact theory as proposed by Hopkins and (2) new experimental results which employ a double pickup method.

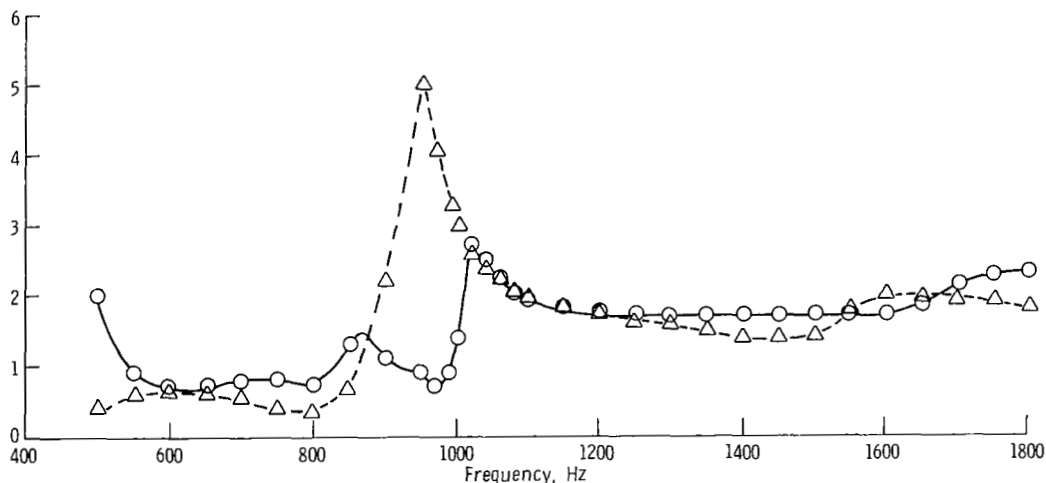
The force-deflection equations used by Hopkins and Fitzgerald for the Hertzian contact stiffness calculations are derived subject to certain restrictive assumptions. The assumption of ideal contact between the two surfaces becomes very important. In Hopkins spherical sample case, the nonlinear stiffness that arises from the deformation of the sphere may be more important than the nonlinear stiffness that arises from the deformation of the surface irregularities of both the sphere and the base plate. Regardless of this uncertainty, the linearization of the assumed load-deflection relation for the purpose of calculating resonant frequencies is itself a questionable procedure since the displacement at resonance is not small. Without supporting evidence which justifies these assumptions, the apparent agreement of Hopkins' predictions would seem to be fortuitous.

Fitzgerald (ref. 5) objects to the Hertzian explanation proposed by Hopkins with a calculation of the resonant frequency of the cylinder-plate experiment. In this calculation, Fitzgerald assumes a linear load-deflection relation of the contact region. This assumption is equivalent to the statement that the cylinder and plate are perfectly welded together so that atom-to-atom contact exists across the entire junction. Thus, Fitzgerald assumes that no surface roughness exists on the machined faces of the cylinder and base plate. Fitzgerald also assumes that these surfaces mate together perfectly and are not contaminated by dirt, dust, oil, lint, etc. Since this assumption is violated in Fitzgerald's experiments (refs. 1, 2, and 5) and at least in Hopkins' bar-plate experiment, the basis of Fitzgerald's first objection is unsound.

Fitzgerald's second objection to all surface contact explanations of his resonance phenomena involves a presentation of new experimental evidence. Fitzgerald (ref. 5) reports experimental data obtained with two phonograph cartridges with which he measures sample motion at two different locations on the sample. An example of the data presented is shown in figure 4. Fitzgerald states that these data show the resonance is not caused by the contact region of sample and shaker.



(a) Variation of pickup voltages at two positions on polytetrafluoroethylene sample with frequency of constant-amplitude driving voltage across piezoelectric agitator A in the ABC method (ref. 1). Room temperature (~25° C).



(b) Variation of pickup voltages at two positions on (100) face of NaCl single-crystal sample with frequency of constant-amplitude driving voltage across piezoelectric agitator A in the ABC method (ref. 1). Room temperature (~25° C).

Figure 4. - Pickup voltages against frequency reported by Fitzgerald (ref. 5) for his double pickup method.

In order to conclude from the data of figure 4 that the sample behaves in a nonrigid manner, it is necessary to assume that the sample moves in the vertical direction only and that the phonograph pickup is only sensitive to this motion. In Fitzgerald's experiment these conditions are not realized.

This experimental method seems to offer no new insight into the question of the origin of Fitzgerald's resonances. The problem is simply that a phonograph pickup does not measure motion in only one direction. Thus, the magnitude and direction of motion cannot be deduced from the magnitude of the output voltage alone.

Our principal objection to Fitzgerald's experiment and his analysis lies in his assumptions concerning the sample-driver interface. Fitzgerald places a sample on the driver without any bonding cement. As a consequence, the sample is supported by the high spots of the sample and driver surfaces such that only a small fraction of the bottom surface of the sample contacts the driver surface. Since the contact region has a small fraction of its area in contact, the contact region also has a small fraction of its ideal (Hertzian) contact stiffness. Any experimental condition which changes the area of contact, changes the stiffness of the contact region, and hence the resonant frequency. Thus, a load-dependent stiffness of the contact region can account for the frequency shifts which Fitzgerald (ref. 5) attributes to stress-dependent intrinsic material properties.

The rough surface contact theory can explain other experimental observations in a reasonable manner. The existence of low kilohertz resonances is expected since the low stiffness of the contact region and the sample mass will form a resonant system in this frequency range. The large amplitude of these resonances results from the small damping associated with the deformation of the sample and driver material in the contact region. For some modes of vibration, the sample may not maintain contact with the driver surface at all times. This may explain the results shown in figure 2. Here the sample has a displacement amplitude many times larger than that of the shaker surface. Under such conditions, rocking, bouncing, and other such modes of vibration are possible which can produce the azimuthal dependence of amplitude which has been reported (see fig. 5). It is also probable that some azimuthal effects result from a coupling of distinct vibrational modes with closely spaced resonant frequencies. Since many samples have azimuthal symmetry, orthogonal tipping modes, for example, will have nearly the same resonant frequency. The pressure of the stylus against a face may produce the needed constraint to determine which mode will dominate for a given angular position. Neither Fitzgerald nor Gotsky and Stearns consider this possibility in analyzing their results.

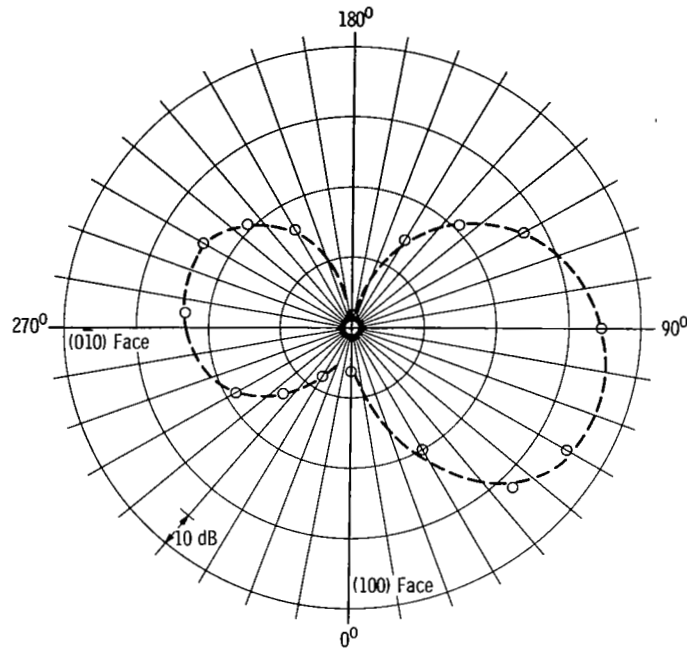


Figure 5. - Polar plot of phonograph pickup voltage (in dB) against angular position of stylus about a square-base NaCl sample. The data are obtained at a single frequency corresponding to an observed resonance mode. Stearns and Gotsky (ref. 3) state that these data are a result of multiple slip. A sample which is rocking on its base may be expected to produce quite similar data.

CONCLUSION

A sample placed on a piezoelectric driver can exhibit one or more resonances in the low to medium audiofrequency range as the frequency of the driver voltage is varied. Resonances of this type are to be expected in this frequency range due to the low stiffness of the contact region. However, if the sample is cemented to the driver surface with a hard cement, no such resonances are observed because the stiffness of the contact region is increased to the extent that the sample mass and the stiffness of contact region will resonate in the high audiofrequency range.

The resonances reported by Fitzgerald and Gotsky and Stearns are produced by a simple spring-mass system. The rigid mass is the sample mass, and the spring is the high compliance coupling between sample and driver. From the results of this study one

may conclude that Fitzgerald's explanation of the resonances cannot be correct, and the slip mechanisms proposed by Gotsky and Stearns are not supported by their experiments.

Lewis Research Center,
National Aeronautics and Space Administration,
Cleveland, Ohio, March 26, 1968,
129-03-15-01-22.

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